



Discovering the Higgs through highly-displaced vertices

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Abstract

We suggest that the Higgs could be discovered at the Tevatron or the LHC (perhaps at the LHCb detector) through decays with one or more substantially displaced vertices from the decay of new neutral particles. This signal may occur with a small but measurable branching fraction in the recently-described “hidden valley” models, hep-ph/0604261; weakly-coupled models with multiple scalars, including those of hep-ph/0511250, can also provide such signals, potentially with a much larger branching fraction. This decay channel may extend the Higgs mass reach for the Tevatron. Unusual combinations of b jets, lepton pairs and/or missing energy may accompany this signal.

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If the Higgs boson is standard-model-like, then 250–1000 Higgs production events (for $m_h = 200$ –120 GeV) [1] have been produced in each Tevatron detector. Much recent work has focused on expanding the Higgs sector and the possible decay channels of the Higgs boson [2–5]. Most of these results have negative implications for the Tevatron and LHC: the signals they generate are as hard as or harder to see than the standard ones. However, if a small but reasonable fraction of Higgs boson decays are unusual and spectacular, this special class of events may allow the Higgs to be found easily, perhaps even with current data. In particular, we focus here on Higgs decays to long-lived neutral particles that may decay at macroscopic distances from the primary vertex.

The purpose of this Letter is to emphasize a simple but perhaps underappreciated point. The Higgs may serve as a window into a new sector of particles uncharged under the standard model gauge group. Its branching fraction to decay to these particles could be substantial. Some of these particles may have long lifetimes and may decay visibly with a displaced vertex. No fine-tuning is required to allow this to occur. The ease of

building models with this phenomenology, and the limited experimental constraints on light neutral long-lived particles, argues that we should not be surprised if the Higgs reveals itself first through such decays. This, along with the fact that the new particles may be tied up with the solution of the hierarchy problem, suggests that searches for displaced vertices and associated multi-jet/multi-lepton final states should be a high priority for the Tevatron and the LHC.

Weakly-interacting models with possibly long-lived neutral particles have arisen before; recent examples were given in [4]. In [7] a strongly-interacting “hidden valley” model, inspired by top–down constructions such as those in [6], was presented, where it was claimed that Higgs mixing with another scalar field allows it to decay to two (or more) new composite electrically-neutral particles (“v-hadrons”) which can in some cases have long lifetimes. Many other models have surely been written down elsewhere. It is easy to construct models where the branching fraction to decays of this type is large enough to see in current Tevatron data. Even more models would allow discovery in this channel toward the end of the Tevatron run or in the early days of the LHC.

Up to this point few Tevatron analyses have looked for long-lived neutral particles, excepting [8,9]; no general program of searches has been undertaken. We are unaware of any organized set of studies for the LHC. We hope this Letter will help

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motivate such a program, which would of course be sensitive to a wide range of models well beyond those discussed below.

Such a program should consider many different final states. The lifetimes of the resonances are not constrained; decays at centimeter and meter scales should equally be considered. Each Higgs decay may produce two or more resonances, with the multiplicity possibly varying from event to event. In many models, the resonances will decay to the heaviest fermion pair available, with branching fractions similar to those of the standard model Higgs. For instance, this is the case in some models of [4,7]. Other resonances may decay flavor-universally, with branching fractions to $\mu^+\mu^-$ and e^+e^- pairs that may be a few percent or more. Decays to gluon pairs are also possible. For instance, a complex Higgs decay in a hidden-valley model could produce, say, four resonances, one decaying promptly to jets, one escaping the detector giving missing energy, and two decaying to $b\bar{b}$, each with a displaced vertex. But this is only one of many possible decay modes in a typical model. Clearly some final states are easier than others for triggering and experimental analysis, but even a few displaced vertices might be the key to finding these decays. The branching fractions need not be large for success; a few fully reconstructed decays, even with poor resolution, would suffice for a claim of evidence of a new resonance consistent with a Higgs boson. The situation may be better still; the branching fractions may be quite large for $m_h \ll 2m_W$. As they may remain measurable even for $m_h \gtrsim 2m_W$, the Tevatron may be considerably more sensitive to heavier Higgs bosons than is usually thought.

Below we will confirm that it is reasonable for branching fractions to neutral long-lived particles to be at observable levels. We will illustrate the simplicity of the model-building involved by briefly considering a few cases. We will start with two weakly-coupled models, one non-supersymmetric, one supersymmetric, with new fundamental scalars. Then we will discuss several hidden valley models with new light composite particles. After some general remarks on more complex signatures, we will conclude with some comments upon the implications for the ongoing and upcoming experiments.

1. Two models with fundamental scalars

To begin, we build a simple scalar theory to illustrate how the Higgs can decay to two scalar resonances X , each of which decays with a displaced vertex to heavy flavor. Consider adding a real scalar X to the standard model, and write the potential

$$V = -\mu^2 H^2 + \lambda H^4 + M^2 X^2 + \kappa X^4 + \zeta X^2 H^2 + aX + bX^3 + cXH^2, \quad (1)$$

where $H^2 \equiv H^\dagger H$. We assume here that TeV-scale physics protects the masses and dimensionful couplings, and that, after electroweak symmetry breaking (EWSB), $m_h > 2m_X$, so that $h \rightarrow XX$ can occur.

When $a = b = c = 0$, the theory has a \mathbf{Z}_2 symmetry under $X \rightarrow -X$. If $\langle X \rangle = 0$, so this symmetry is not spontaneously

broken, then X is stable, and the decay $h \rightarrow XX$ will be invisible. For a light Higgs, its branching fraction $\sim |\zeta v / y_b m_h|^2$ need not be small; here $v = \sqrt{2}\langle H \rangle$ and y_b is the b -quark Yukawa coupling. If instead a, b, c are nonzero but small, the \mathbf{Z}_2 symmetry is explicitly but softly broken. It is then technically natural to have small mixing, after EWSB, between X and H . While the mixing does not much affect H decays, it drastically affects X decays (since without it X is stable). If the low-mass eigenstate is of the form $|X\rangle + \epsilon|h\rangle$, the decay rate for X is $\Gamma_X = \epsilon^2 \Gamma_h$, and its branching fractions are those of the Higgs. Since ϵ is related to the breaking of the \mathbf{Z}_2 symmetry, it can naturally be small; the decays may be prompt, invisibly long, or anything between.

If ϵ were not small, and the X decays were prompt, the above model would have similar phenomenology to the next-to-minimal supersymmetric standard model (NMSSM) in certain regimes [2,4] where the Higgs branching fraction to light neutral states can be large. We have not attempted to modify the NMSSM itself to obtain long-lived states (but see [4]). Long-lived states in Higgs decays can also be obtained in a supersymmetric variant of the model in Eq. (1). Consider the MSSM with electroweak singlet scalars S and X , and superpotential

$$W = \lambda S H_u H_d + \eta S^3 + \kappa S X X + b X^3. \quad (2)$$

If $b = 0$, this model has an $X \rightarrow -X$ symmetry. After EWSB and supersymmetry (SUSY) breaking, S , H_u and H_d acquire expectation values. We assume $m_h > 2m_X$. We may (naively) require $\lambda\kappa \lesssim 1/20$ to avoid a large X mass; even so, since $y_b \ll 1$, we can have $\text{Br}(h \rightarrow XX) \propto |\lambda\kappa v / y_b m_h|^2$ of order one. If $b \neq 0$, then after SUSY breaking a loop effect will allow X to mix with S , and thereby with h , with a mixing angle $\epsilon \lesssim |\kappa b| / 16\pi^2$. Then X can decay to heavy flavor with a long lifetime. The angle ϵ may be further suppressed if the mass splitting between X and its fermion partner ψ_X is rather small, as is the case in some SUSY-breaking scenarios. Thus there is no obstruction to building natural models with a Higgs that often decays in this fashion.

If $\text{Br}(h \rightarrow XX) \gtrsim 0.1$, displaced τ pairs may be detectable; they are lightly constrained by [8]. If in addition $m_X < 2m_b$, so that $\text{Br}(X \rightarrow \tau^+\tau^-) \sim 1$, then [8] is a more significant constraint. More complex decays, analogous to those in [4], can also potentially occur in this model; we will briefly return to this later.

For a Higgs with $m_h \gtrsim 2m_W$, $\text{Br}(h \rightarrow XX) \propto |\lambda\kappa v^2 / m_h^2|^2$ is perhaps of order one percent or so; also Γ_h is larger now, so a smaller ϵ is needed for displaced vertices to result. If this were the case, the reach of the Tevatron would extend toward much higher m_h than is normally considered. Despite a smaller rate and trigger efficiency, events with displaced vertices may well be more important than WW decays to leptons, for which there is an irreducible background and no possibility of kinematic reconstruction. Also, in two-Higgs doublet models there is a CP-odd scalar A^0 which is produced in $gg \rightarrow A^0$ but which cannot decay to WW or ZZ . Its discovery may be made much easier by exotic decays with a large branching fraction.

2. Composite resonances in hidden-valley models

We now turn to a different class of models. The phenomenology of confining hidden valley models was recently outlined in [7]. These models can show qualitatively similar signals to the theories just discussed, though the origin of the signals is quite different. We will now see that the illustrative models of [7] can give the Higgs a substantial branching fraction to long-lived neutral resonances.

We briefly summarize the particular hidden-valley models that were explored in [7]. (Hidden valleys—sectors with a non-Abelian gauge group under which no standard model matter is charged, which couple weakly to the standard model via higher dimension operators, and which have a mass gap—are common in string constructions of the standard model [6], though string theory is of course not required.) The “v-sector” consists of a confining gauge group that makes v-hadrons out of its v-quarks, in analogy with QCD. The only couplings between the v-sector and the standard model occur through a heavy Z' (which has coupling g' and mass $m_{Z'} = 2\sqrt{2}g'\langle\phi\rangle$, where ϕ is a scalar that also gives mass to v-quarks) and through possible mixing (as in [3]) between ϕ and the Higgs. If such mixing is present, a Higgs decay to v-hadrons, shown in Fig. 1, can be followed by the late decay of the v-hadrons via the heavy Z' . LEP I constraints conservatively require $\hat{v} \equiv \sqrt{2}\langle\phi\rangle > 5$ TeV, though this can often be relaxed, perhaps to 2–3 TeV, because of conservation laws that render some Z decays invisible or forbidden. In these simple models, lifetimes for light pseudoscalars (which decay to heavy flavor) of mass ~ 20 (40) GeV are of order 100 ps (1 ps); this includes the π_v^0 [η_v'] for two [one] light v-flavors. However, other v-hadrons could give displaced vertices if an approximately-conserved quantum number delays their decays. Additional details are given in [7].

The potential for the scalar fields takes the form

$$V = -\mu^2|H|^2 - \hat{\mu}^2|\phi|^2 + \lambda|H|^4 + \tau|\phi|^4 + \zeta|\phi|^2|H|^2. \quad (3)$$

Since $\gamma \equiv v/\hat{v} \sim 1/10 - 1/20$, we can set $\zeta \sim \lambda\gamma^2$, $\tau \sim \lambda\gamma^2$, and then obtain a mixing angle θ which is naturally of order 0.1 or larger. Extreme fine-tuning of parameters (at the classical level) is not required. Adjusting λ and μ , we can obtain acceptable values for m_h and v .

Given that the mixing angle is not too small, let us now estimate the branching fraction. The produced Higgs state is $\cos\theta|h\rangle + \sin\theta|\phi\rangle$, with $\sin\theta \lesssim 0.3$. The production process is slightly suppressed, by $\cos^2\theta$. Let y_0 be the Yukawa coupling of $\phi Q\bar{Q}$ where Q is the heaviest v-quark allowed kinemati-

cally; then (assuming only minor phase space suppression in the $h \rightarrow Q\bar{Q}$ decay) the branching fraction to v-hadrons for a Higgs below 140 GeV is naively of order

$$\frac{y_0^2}{y_b^2} \sin^2\theta \approx \left[\frac{m_Q}{m_b} \frac{v}{\hat{v}} \sin\theta \right]^2. \quad (4)$$

As a figure of merit, requiring a branching fraction of 1 percent would require $\sin\theta \gtrsim m_b/m_Q$. However, there are large v-hadronic corrections to this result [10]. We will not discuss this at length, but suffice it to say that for the exclusive channel $h \rightarrow \pi_v^0 \pi_v^0$ a conservative estimate is given by replacing m_Q with $m_\pi^2/3m_h$ in (4); this is a considerable underestimate in models with additional heavy v-quarks [10]. If other v-hadron decay channels are available, they may be favored over $\pi_v \pi_v$; some of these may give displaced vertices as well [7].

The v-hadronic branching fraction of the Higgs may be larger in a model with two ϕ fields (with expectation values \hat{v}_1 and \hat{v}_2) and a single Higgs doublet H . For instance, if $\tan\beta_v \equiv \hat{v}_2/\hat{v}_1 \sim 20$, so that $\hat{v}_1 \sim v$, and if ϕ_1 couples to Q , then the factor v/\hat{v} in (4) is enhanced by $\tan\beta_v$. The π_v^0 decay still proceeds through the Z' propagator, and its lifetime remains long. However, if the standard model sector also has two Higgs doublets H_1, H_2 , as in any supersymmetric model, then mixing between the CP-odd scalars in the two sectors can allow the π_v^0 to decay more rapidly, eliminating the displaced vertices. This can be avoided only if $m_{\pi_v} < 2m_b$, or if the standard model sector's CP-odd scalar A^0 is heavier than a TeV or more, suppressing its mixing angle relative to θ by $\sim m_h^2/m_A^2$. However we emphasize that this constraint is special to the simplest models.

In fact it is instructive to consider a simple supersymmetric generalization of the hidden-valley model in [7]. Minimally supersymmetrizing the models of [7] requires two Higgs multiplets H_u and H_d and two new v-Higgs multiplets ϕ_1 and ϕ_2 . The D-term of the new $U(1)$ induces mixing between the Higgses in this model, but generally is either too small or generates a large shift in m_h that must be cancelled elsewhere. An F-term is therefore necessary to induce larger mixing. If we add a singlet S which couples through the superpotential

$$W = \lambda S H_u H_d + \eta S^3 + \kappa S \phi_1 \phi_2 \quad (5)$$

then it is possible to arrange for substantial h – ϕ mixing. However, to keep the π_v^0 long-lived requires the CP-odd scalar A to be heavy or its mixing angle to be small. A small mixing angle can still allow branching fractions large enough to see at the LHC, but to reach branching fractions of one percent while still retaining visibly-displaced π_v^0 decays requires uncomfortable tuning. Nevertheless, one should not conclude that supersymmetric hidden-valley models disfavor decays of this type at the Tevatron. SUSY also may introduce flavor-changing neutral currents through off-diagonal v-squark mass-squared terms or A-terms, whose size depends on the details of supersymmetry breaking. Such terms could allow an otherwise stable v-hadron, such as the π_v^+ in the model of [7], to decay to $b\bar{b}$ with a long lifetime [7], even if the A is light. (This can occur in the model of [7] for $q_+ = -2$.) In other words, the π_v^+

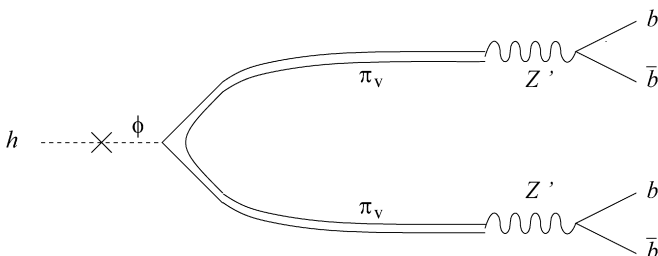


Fig. 1. Higgs decay to v-hadrons, each of which decays to $b\bar{b}$.

lifetime is determined through the same mechanism used in the weakly-coupled models above: a weakly-broken approximate symmetry. In turn, this relaxes the constraint on m_A and its mixing angle, and therefore can allow $\text{Br}(h \rightarrow \pi_v^+ \pi_v^-)$ to be much larger. The increased number of events widens the range of π_v^+ lifetimes for which a few displaced vertices could be observed now or in the near future.

Of course this is just one of many hidden-valley models. It provides an existence proof that the Tevatron may be able to observe the Higgs in this decay mode, and should be sufficient to motivate an experimental search for $h \rightarrow (b\bar{b})(b\bar{b})$ with displaced vertices. Tau pairs should also be sought. But we must be prepared for other phenomenology as well [7]. A systematic classification of the most promising final states is needed, though it will inevitably suffer from considerable model-dependence. Here we limit ourselves to some general remarks.

3. More complex final states

In weakly coupled models, including those of [4] and that of Eq. (2), a more complicated spectrum will allow a cascade of immediate decays, leading to a final state with several long-lived particles. In the hidden valley models, the Higgs will preferentially decay to the heaviest kinematically allowed v -quarks. These in turn form v -hadrons which may then decay to multiple v -hadrons made from lighter v -quarks; or, if the confinement scale is sufficiently low compared to m_h , showering and hadronization may occur, resulting in multi- v -hadron final states [7]. (In such a scenario, where the production rate is increased by heavier v -quark masses, but the final state has a large multiplicity of v -hadrons whose decay rates are decreased by lighter v -quark masses, the probability of seeing displaced vertices is enhanced.) The multiple resonances produced in these Higgs decays may decay with a variety of lifetimes. Not all the resonances may decay preferentially to heavy flavor, and some may have complex decays. Some unusual possibilities are discussed briefly in [7].

If many or most Higgs decays of this type contain invisible particles or have resonances decaying to soft particles, reconstructing the Higgs resonance using these events may be very challenging. Even so, the kinematics of a large sample of events may allow a rough estimate of the mass scale involved and hint that the initial state is gg . At the other extreme, if all the new particles decay visibly but promptly, as in [2,4], then even selecting events may be extremely difficult. This unfortunate outcome cannot be excluded, but neither is there any reason to expect the worst.

4. Implications

One could explore many more examples, but this would merely bolster a point that should already be clear. With possibly hundreds of Higgs boson events on tape, various searches for displaced vertices in Tevatron data could be undertaken now. Meanwhile, it seems to us that the LHC experiments should prioritize ensuring that tracking software is efficient at detect-

ing displaced vertices, especially those involving muons and/or multiple charged tracks. Both CMS and ATLAS will implement a displaced-vertex trigger (often called a “ b -trigger”) as part of their high-level triggers. We would suggest that the upper-limit on the vertex displacement be extended as far as possible and not be constrained by expectations from b decays. It may also be valuable to consider special-purpose triggers for (1) highly-displaced many-track vertices including a muon or electron, (2) hard calorimeter jets with no stiff tracks pointing from the pixel detector, and/or (3) calorimeter jets with no electromagnetic energy or associated stiff tracks. To the extent detector effects and QCD backgrounds make it difficult to use such objects in triggering, one could consider requiring two such objects simultaneously. This should still be efficient, since two or more displaced vertices per event will be common in many models. In general, since it appears that light, long-lived neutral resonances (without charged resonances) are a common feature of reasonable models, there are good reasons to maximize the sensitivity of the LHC experiments to their phenomenology. Indeed it is possible that the LHCb experiment is ideally suited for detecting and studying such states.

We have argued that it is possible in a diverse array of models for the Higgs to decay to two or more neutral resonances, with a wide range of possible final states. Some of these resonances may decay with a displaced vertex anywhere in the detector. The branching fractions for these decays may allow them to be discovered at the Tevatron with current or future data, and easily found at the LHC; this is especially true for a light Higgs but may even be so for $m_h \gtrsim 2m_W$. Moreover, signs of other new phenomena, such as those of [7], or perhaps supersymmetry itself [11], could be discovered first in such searches. We urge the Tevatron and LHC communities to take this possibility seriously and undertake a wide array of searches for displaced vertices. A comprehensive program is needed, not only because of the many possibilities offered by different models, but also because, even within one model, the Higgs may have many decay modes. It may be that only in the combination of multiple analyses can the Higgs boson be discovered in the immediate future. Although many of these analyses will be technically difficult and time-consuming, it would seem that the possibility of discovering the Higgs more rapidly than typically expected provides sufficient motivation.

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